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Productivity Analysis of Tubular Solar Still with Heat Absorption Material

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Abstract -The integration of solar stills with materials capable maximum heat absorption and transfer heat is an effective option for producing potable water from brackish water. Nevertheless, no single organic phase change material exhibits all the necessary advantageous properties, such as a particular temperature of melting and latent heat of fusion, to function well in a solar still under varying environmental circumstances. A tubular solar still comprising five copper cylinders filled with paraffin wax has shown a significant increase in distillation yield. The impact of depth of basin water on performance of stills was examined (steel balls with water depth of 4 cm) using MTSS under environmental conditions for city of Bhopal located in Madhya Pradesh, India. The result revealed a cumulative yield for CTSS and MTSS as approximately 4.2 and 5.9 kg/m^2 respectively. The result reveals that total hourly yields for CTSS and MTSS are approximately 1.28 and 1.68 kg/m^2 respectively. The production of solar distillate rose by 48.8% with the use of steel balls in MTSS, in contrast to the basic scenario without steel balls, where the output of solar distillate was 60.2% in CTSS.

Keywords **–** Steel balls, CTSS, MSTT, Solar Energy, Water

1. INTRODUCTION

A solar still is a maneuver used to purify water through a simple and passive distillation process using solar energy. It is typically designed to be used in regions with limited availability of safe and clean drinking water, such as arid and remote areas. Solar stills are particularly useful in situations where other water purification methods like boiling, filtration, or chemical treatment are not readily available or practical.

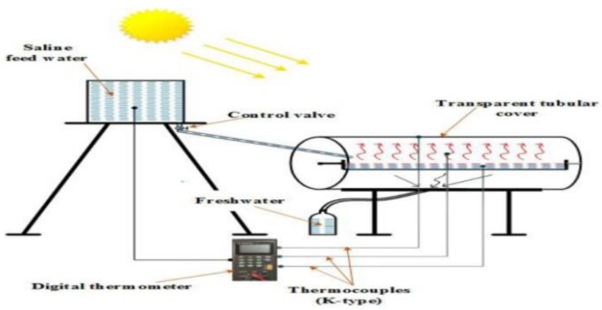

Figure 1 Schematic diagram of TSS experimental set up [1].

Providing fresh water is a major global concern. The steady increase in population and economic activity raises the need for freshwater, placing a heavy burden on the world's natural water supplies. Over 3.2 billion people worldwide are estimated to be living in water-scarce circumstances[2]. The agencies worldwide have reported between 2009 and 2017, the world's industrial freshwater consumption nearly doubled, from 58.6 to 117 million cubic meter per day [3]. The ongoing need for energy and water will cause global warming to increase Pollution and pollution in the absence of the development of sustainable substitutes for the production of energy and water. More desalination is required due to the sharp rise in freshwater demand.[4] There are two primary types of procedures that are now employed for desalinating saline water: thermal and membrane techniques. In thermal procedures, the saline water is evaporated with a significant amount of heat, and the vapor condenses on colder surfaces. Numerous heat sources, including fossil fuels, coal, geothermal energy, nuclear power, waste heat from various high-temperature industrial Heat can be produced using solar energy and applications (power plants).[5] Multi-stage flash (MSF) and multiple effect distillation are common techniques for thermal desalination. For large productivity facilities, particularly in the Gulf region, (MED), thermal vapor compression (TVC), mechanical vapor compression (MVC), and MSF are typically utilized. The second category of membrane technology uses thin membranes to reduce the salinity of water to a suitable level without the requirement for an evaporation or condensation process. Electro dialysis (ED) followed by reverse osmosis (RO) is a frequently utilized membrane method. RO is best suited for small and moderate demands. The foundation of the membrane distillation (MD) process is a fusion of membrane and thermal procedures. By gently the salt water is heated to encourage vapor penetration via the narrow hydrophobic membranes' holes, salinity is separated from the saline water. Low temperatures, as low as 40 °C, were needed for this process and is available (using solar energy that is direct[4]. While the cost of solar stills climbed significantly to $11.8.[6]

TSS design facilitates its effortless installation at the parabolic concentrator's focal line, resulting in elevated temperatures that reach the boiling point. larger temperatures can cause a larger evaporation rate, which can be effectively condensed by the larger inner tube surface area of the condenser. Lowering the cost of solar tracking is crucial for the TSS technology to

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develop quickly. A minimum-cost sun monitoring control system for TSS was proposed[7]. They employed LDR and the sun-path computation technique. They were able to get the device down to $76. For the TSS application, has proposed an inexpensive solar tracking device using parabolic concentrators architecture. Two little light-dependent resistors (LDRs) were used to regulate a tiny motor for all-in-one solar tracking system. Their suggested method had a low-speed cost of $73.25/m^2 and reduced the CPL by 43.1%.[8].

Only a small number of the last ten years' worth of studies have focused on the economics of producing devices with lower cost per liter (CPL) in order to produce TSS devices for increased freshwater productivity and efficiency. Numerous methods and factors, including heat-storage materials with multiple effects, trough geometry, tube cooling, and heat recovery, and the use of atmospheric water harvesting (AWH), were considered during the development of the TSS. Furthermore, The price of TSS per liter (CPL) varies from $0.0061 to $0.2, according to economic study. The impact of the several impacts on the multi-effect TSS's productivity and CPL was examined [9]. According to their findings, freshwater yield increases with larger CPL when the TSS has more than three effects resulting in two to three consequences.

Vacuum was employed with a triple-effect TSS that had an evacuated solar collector and a cascade feed. At 40 kPa, the greatest TSS production of 7.056 L/day. Hybrid graphene oxide nanoparticles (NPCM) with phase change material (PCM) were employed with the TSS [10]. Their findings indicated a yield boost of 117%. New PCM-tubes were created in order to increase TSS productivity[11].Within the TSS's half-cylindrical trough, they used 12-PCM tubes. According to their findings, there was a 21.8% decrease in CPL (0.00782) and a 40.51% rise in freshwater yield (5.55 L/m^{2}day). Furthermore, a number of factors influencing TSS productivity were examined, including mass, heat transfer, and the tube's surface cooling. They claimed that productivity rose by 30% when nanomaterials like zinc oxide were used. Furthermore, they suggested that future research take wind resistance and meteorological circumstances into account. The employed standard and operational constraints of TSS, including the temperatures of the glass cover and saline water, as well as the weather[12].. To increase TSS productivity, they introduced the numerous TSS methodologies.They stressed how crucial it is to have the correct TSS design proportions. A thorough investigation of the performance, thermal, economic, and sophisticated designs of the TSS was presented[13]. They

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came to the conclusion that horizontal TSS is more effective than vertical TSS. Recent advances in basin and tubular solar stills were recently thoroughly evaluated[14]..

A tubular solar still is a state-of-the-art water purification system that harnesses solar energy to distill water, making it suitable for drinking[9]. It consists of a transparent tubular chamber, typically made of glass or durable plastic, which acts as both the solar collector and evaporation chamber. Contaminated water is introduced into the bottom of the tube, where sunlight heats it, causing evaporation[15]. The vapor rises and condenses on the cooler interior surface of the tube, then collects in a clean reservoir. This procedure effectively eliminates contaminants like salts, bacteria, and heavy metals[16].

The tubular design optimizes sunlight absorption by providing a larger surface area and enabling a greenhouse effect, which enhances evaporation rates. Additionally, the cylindrical shape allows for easy rotation, ensuring maximum exposure to the sun throughout the day. Tubular solar stills are compact, cost-effective, and environmentally friendly, making them ideal for remote or arid regions where clean water is scarce.

The results indicate that solar stills are environmentally sustainable desalination methods distinguished by their operational and design simplicity. Nevertheless, the solar energy conversion efficiency of existing desalination methods is below 10% percent, underscoring the need for innovations to improve freshwater output.

The current study demonstrates that the tubular solar still made of an acrylic glass material with a high light transmissibility boosts saline water productivity. In the ongoing review, Acrylic was utilized as the gathering surfaces to tentatively examine the CTSS and MTSS. In a similar paraffin wax , it is suggested that the CTSS and MTSS should investigate the potential advantages of employing a variety of phase change materials. During the experimental studies, it was noticed that some of the condensed droplets fell into the basin, which may influence the MTSS productivity. This requires additional investigation, and CTSS should investigate potential solutions to counteract this loss at night caused by atmospheric temperature. Therefore, MTSS was utilized with steel balls that were kept in the basin. It has likewise been noticed that the steel balls gives the most elevated level of tubular solar still efficiency, however since its production required extensive expertise and time, it is exhorted that an affordable assembling technique be examined to deliver the low-thickness cylindrical glass cover for the MTSS. In this study maximum temperature 39.9^{0}C at 1 pm reached for water evaporation and find maximum hourly yield, cumulative yield and thermal efficiency

Research on a tubular solar still using sensible heat materials assumes ideal cylindrical geometry with uniform heat transfer and perfect insulation. Steel balls properties (thermal conductivity, specific heat) are constant and homogeneous. Solar intensity is steady or averaged, with no shading or weather disruptions. Heat losses through radiation or convection are negligible, and water properties remain constant. The system operates continuously, efficiently converting absorbed heat into water evaporation and condensation. External

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environmental effects like temperature variations are minimized. Measurements are accurate, and results are representative of real-world conditions, focusing on evaluating sensible heat materials impact on solar still performance.

2. EXPERIMENTAL

The cylindrical tube acrylic glass used with height of 100 cm and a diameter of 50 cm. The extended region of the CTSS and MTSS was 5000 cm^2. The length and width of the trough are 86 cm and 38 cm, respectively, across the CTSS and MTSS and trough is made from steel material with black paint painted for better heat absorption. Thickness of trough sheet is 0.15cm

Table 1. Exiting and Modified solar still

Sr. no.	Experimental Date	Still Type	
01	16-06-2024	Conventional	Modified
		CTSS (4 cm basin water depth without steel balls	MTSS (4 cm basin water depth with steel balls

3. METHODOLOGY

The Between hours of 10:00 am and 5:00 pm in June 2024, experimental observations were taken. The encompassing temperature (Ta), temperature of basin water (Tb), temperature of vapor temperature (Tv), and solar radiation intensity (Ir) were estimated all the while during the trials.
At depths of 4 cm, the temperature of the basin's water was measured. K-type thermocouples were used to measure all these temperatures, and a digital data logger was used to record the thermocouple outputs. An analog Pyranometer (PYRA300) was used to measure solar radiation's intensity (Ir). The consolidated fresh water was gathered in an aligned bottle. Solar radiation intensity, freshwater productivity, and various current measuring temperatures were tracked every hour.
Depending on the state of the climate conditions the intensity of the solar radiation varied from 440 to 810 W/m^2. The performances of the solar still with steel balls and the conventional solar still are tested at the same basin water depth of 4 cm and under the same ambient conditions at 39.9^{0}C temperature[3].

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Table 2 Uncertainty error for various experimental measuring devices

Device	Accuracy	Range	Error
Solarimeter	± 1w/m^2	0-5000 w/m^2	0.15%
Thermocouples	±1 ^{0}C	-200:1250 ^{0}C	1.81%
Calibrated flask	±5ml	0-2000 ml	1.175%

Figure 2 Steel balls spread in trough

5kg steel balls , each with a diameter of 1 cm were used as shown in Fig.1 (a) Absorber area was primarily augmented by steel balls. This resulted in higher intensity of sunlight absorbed for better heat release during lowered sunlight. Steel balls are used to store and release heat, improving the efficiency of solar stills during periods of low solar radiation and Their high thermal conductivity helps in uniform heat distribution across the basin.

Table 3 Thermo physical parameters of steel ball used

Steel Ball	Melting Temperature (^{0}C)	Specific Heat J/kg·K	Thermal Conductivity W/mK
SB	1510	500	60

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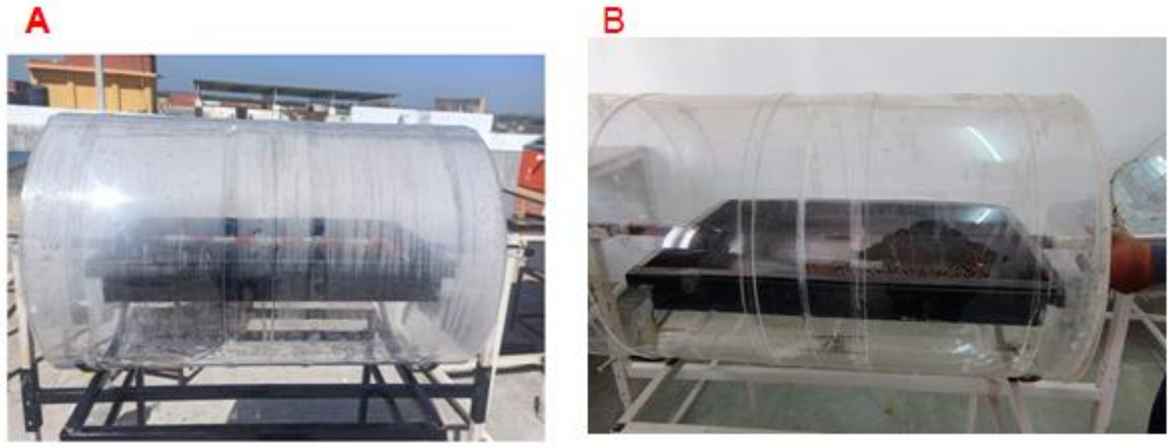

Figure 3 (a) & (b) Conventional Tubular solar still & Modified Tubular solar still with steel balls

In CTSS absence of effective thermal storage means heat energy is wasted when sunlight is unavailable, limiting productivity The system's output is low, particularly under suboptimal sunlight conditions or in regions with fluctuating solar intensity. By presenting these design elements and performance drawbacks, readers can better appreciate the motivations behind the modifications introduced in the MTSS. These improvements, such as integrating steel balls for thermal energy storage and using advanced materials, directly address these limitations, making the MTSS a more efficient and reliable solution.

4. RESULTS AND DISCUSSION

Hypothetical Analysis Thermal Energy:

Daily efficiency of the solar still can be examined using the following equation to determine the performance enhancement achieved by incorporating various modifications[17]. (1)

$$\eta_d = \frac{\sum \mathrm{hfg} \times \mathrm{m_p}}{\sum \mathrm{A} \times \mathrm{I(t)}}$$

Where, mp denotes the hourly new water supply (Kg/s), hf_g represents the latent heat of vaporization (kJ/kg), I(t) indicates the average solar radiation value (KW/m^2), and An signifies the projected glass surface area (m^2)[14].

$$h_{fg} = 10^3[2501.9 - 2.40706T_w + 1.192217 \times 10^{-3}{T_w}^2 - 1.5863 \times 10^{-5}\,{T_w}^3] \quad (2)$$

Where, T_w is the water temperature (°C)

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This experimental investigation assessed the hourly collective yield, hourly freshwater output, and thermal efficiency of the Conventional Tubular Solar Still (CTSS) and the Modified Tubular Solar Still (MTSS). The two distinct examples of CTSS and MTSS. The performance of all quantified instances were evaluated by hourly measurements of several parameters, including solar radiation, water temperature, basin temperature, steel balls , ambient temperature, and fresh water production.

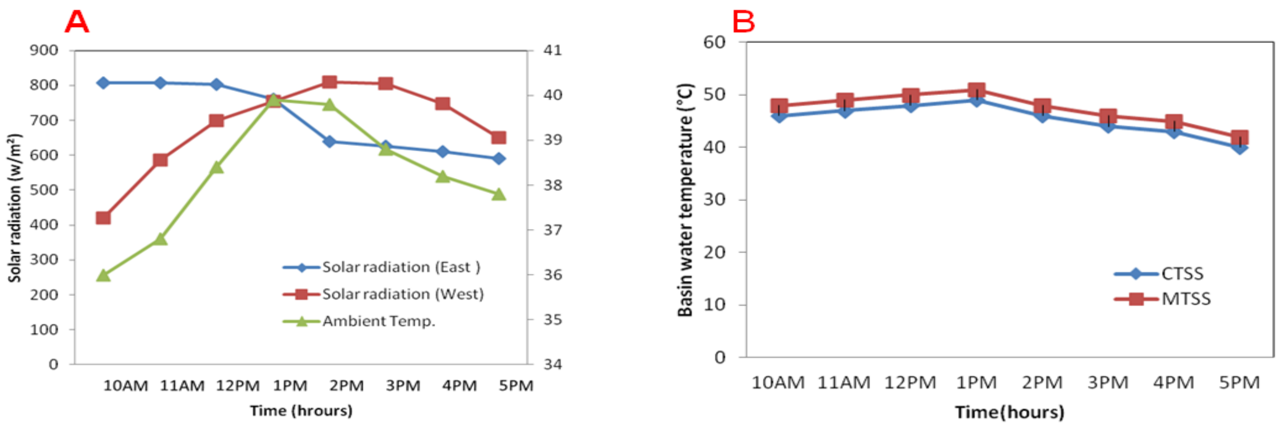

Figure 4 (a) & (b) Solar Radiation v/s Ambient Temperature with time and Basin water temperature and ambient temperature with time

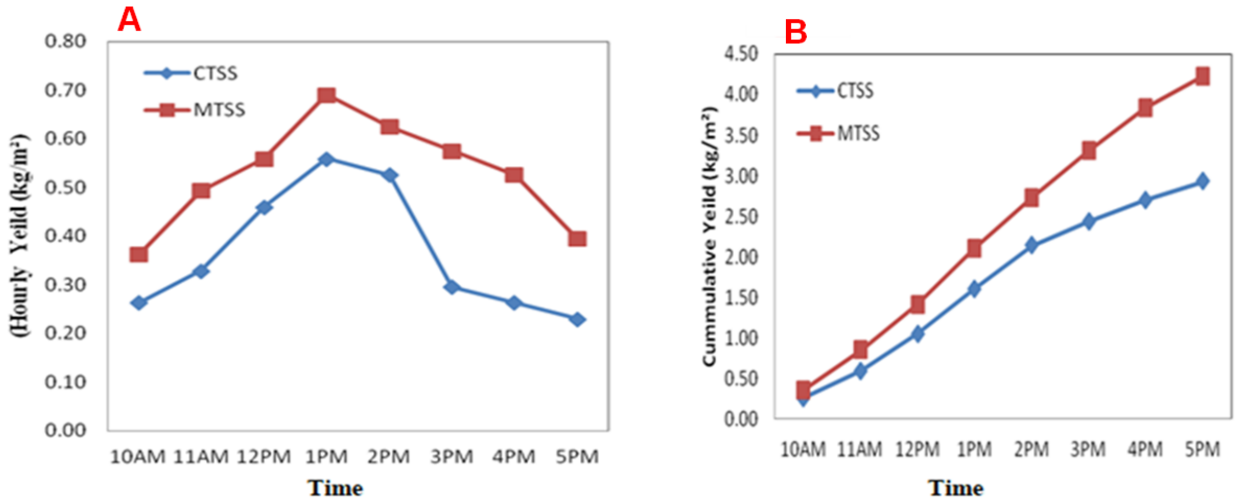

Figure 5 (a) & (b) Hourly cumulative yields of MTSS and CTSS & Hourly freshwater yield of MTSS and CTSS

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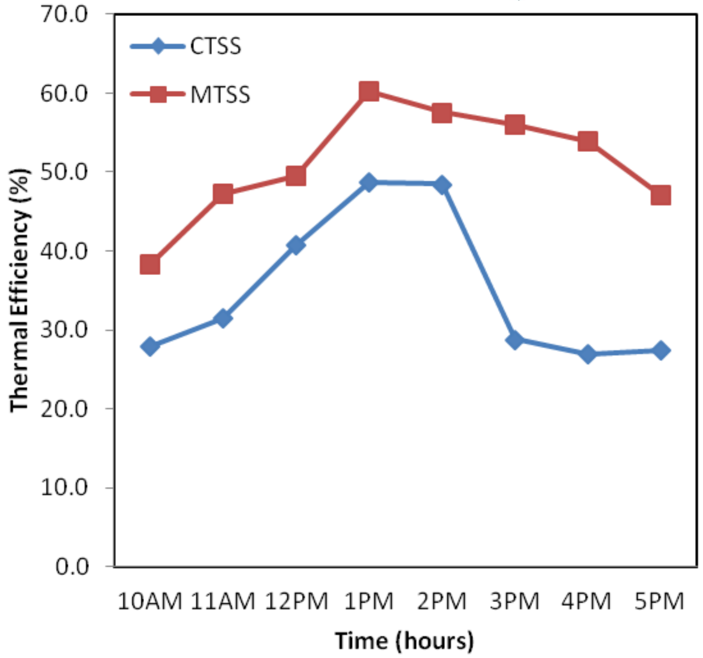

Figure 6 Thermal efficiency of CTSS and MTSS

Execution of rounded sunlight based still with altered tubular solar still. When selecting the materials for the current project, the most important considerations were availability, affordability, resistance to sunlight, transparency, and adaptability to the outdoor environment. As CTSS and MTSS covers, this work made use of Acrylic and steel balls material for MTSS. The analyses were completed utilizing two unique CTSS setups with comparable determinations, yet involving one different material like steel balls for the time of one month. The research can be used to make the following inferences.

6. CONCLUSIONS

The result revealed a cumulative yield for CTSS and MTSS as approximately 4.2 and 5.9 kg/m^2 respectively. The result reveals that total hourly yields for CTSS and MTSS are approximately 1.28 and 1.68 kg/m^2 respectively. The production of solar distillate rose by 48.8% with the use of steel balls in MTSS, in contrast to the basic scenario without steel balls, where the output of solar distillate was 60.2% in CTSS.

Desalinated water production often peaks during summer months due to increased demand for water. Seasonal factors like higher temperatures lead to greater water consumption for drinking, irrigation, and cooling purposes. Additionally, in regions with limited natural freshwater resources, desalination plants ramp up production during summer to meet this increased demand. Explaining this context would clarify the connection between seasonal factors and the operational adjustments of desalination plants.

A summary of the main technical enhancements introduced in the Modified Tubular Solar Still (MTSS) would be valuable. For instance, highlighting the role of materials capable of changing the sensible heat materials , steel balls in enhancing storage of thermal energy and extending operational efficiency, the use of advanced materials to improve durability and heat retention, and any design modifications that boost water evaporation and condensation rates would effectively underscore the value of these improvements.

Explore alternative steel balls with higher thermal conductivity capacities, better compatibility with the system, and reduced costs to enhance overall efficiency. Investigate the scalability of the design for larger installations and assess how the system can be integrated with other renewable energy technologies, such as photovoltaic panels, to maximize output. Incorporate smart sensors and automated control systems to monitor and regulate the still's performance in real time, ensuring optimal operation.

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NOMENCLATURE

CTSS	Conventional tubular solar still
MTSS	Modified tubular solar still
h_{fg}	Evaporation latent heat (KJ/Kg)
m_p	Yield of fresh water per hour (Kg/s)
A	Glass surface area (m^2)
A_b	Area of basin (m^2)
I(t)	Intensity of solar radiation (KW/m^2)
T_w	Water temperature (◦C)
T_b	Basin liner temperature (˚C)
T_{gi}	Internal glass cover temperature (˚C)
hc,w-g	Heat transfer coefficient through convection
$h_{e,w-g}$	Evaporative heat transfer coefficient
ht	Heat transfer coefficient (Total)
P_w	Vapor pressure (partial) of surface of water (Pa)
P_g	Vapor pressure (partial) of inner glass (Pa)
SB	Steel balls
Greek letters	
η_d	Daily average energy efficiency

Author

Neeraj Yadav: Conceptualization, methodology, original draft writing

Dr. Namish Mehta: Methodology, investigation, supervision, editing

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